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Imaging Detector Systems for Soft X-ray and Proton Radiography

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ABSTRACT

Multi-pulse imaging systems have been developed for recording images from pulsed X-ray and proton radiographic sources. The number of successive images for x-ray radiography is limited to four being generated by 25ns, pulsed sources in a close positioned geometry. The number of proton images are provided by the number of proton bursts (~ 60ns) delivered to the radiographic system. In both cases the radiation to light converter is a thin LSO crystal. The radiographic image formed is relayed by a direct, coherent bundle or lens coupling to a variety of electronic shuttered, cooled CCD cameras.

The X-ray system is optimized for detecting bremmstrahlung, reflection geometry generated X-rays with end point energies below 300keV. This has resulted in less than 200μm thick LSO converters which are 25x25mm^2. The converter is attached to a UV transmitting fiberoptic which in turn is directly coupled to a coherent bundle. The image is relayed to a 25mm microchannel plate image intensifier attached to a 4 image framing camera. The framing camera image is recorded by a 1600x1600 pixel, cooled CCD camera.

The current proton radiography imaging system for dynamic experiments is based on a system of seven individual high-resolution CCD cameras, each with its own optical relay and fast shuttering. The image of the radiographed object is formed on a 1.7mm thick tiles of LSO scintillator. The rapid shuttering for each of the CCD's is accomplished via proximity-focussed planar diodes (PPD), which require application of 300-to-500 ns long, 12kV pulses to the PPD from a dedicated HV pulser. The diodes are fiber-optically coupled to the front face of the CCD chips. For each time-frame a separate CCD assembly is required. The detection quantum efficiency (DQE) of the system is about 0.4. This is due to the lens coupling inefficiency, the necessary demagnification (typically between 5:1 and 3:1) in the system optics, and the planar-diode photo-cathode quantum efficiency (QE) (of ~15%). More recently, we have incorporated a series of 4 or 9 image framing cameras to provide an increased number of images. These have been coupled to cooled CCD cameras as readouts.

A detailed description of the x-ray and proton radiographic imaging systems are discussed as well as observed limitations in performance. A number of improvements are also being developed which will be described.

Keywords: electro-optic shuttering, radiography

1. INTRODUCTION

Historically, utilization of electronic imaging systems for recording images in radiographic experiments has been limited. This has been in part due to a lack of resolution achievable over the required field of view, a lack of radiation sensitivity, and a limited dynamic range in the electronic imaging system. The application of 0.2 to 2mm thick sheets of LSO or mixed YSO/LSO provide a high visible photon output per incident x-ray or minimum ionizing proton which is then efficiently coupled to electronically shuttered, cooled CCD cameras. The combination of electronic shutter and CCD camera results in better resolution and dynamic range than is readily achievable with film. The ability to record multiple images due to electronic shuttering capabilities provides a unique capability not achievable with recently developed phosphor screens.

The present paper will describe two systems developed to permit multi-image radiography for characterizing the dynamic behavior of objects of interest utilizing multiple pulses of x-rays ($\leq$ 150 KeV) or 800 MeV protons. Although the x-ray system is optimized for very thin objects ($\leq$ 100mg/cm^2) and the proton system for areal densities $\leq$ 40g/cm^2 , the radiation-to-light converters and electro-optic recording systems are very similar.

2. The X-ray System

Four closely spaced x-ray sources each provide $\cong$ 15mr @ 1m with a pulse duration of 30ns and a spot size of a few mm[1]. The pulse separation is determined by independently triggering the sources. Typical pulse time separations are $\geq$ 1μs. The sources are placed relative to the object and image planes to give an effective spot size of < 200μm. To provide enhanced contrast for areal densities $\leq$ 100mg/cm^2 the LSO or mixed YSO/LSO scintillators are bonded to a fiberoptic and polished to a thickness of $\cong$ 200μm and then coated with a thin reflective aluminum coating. An overview of the image relay and electronic recording system are shown in Figure 1.

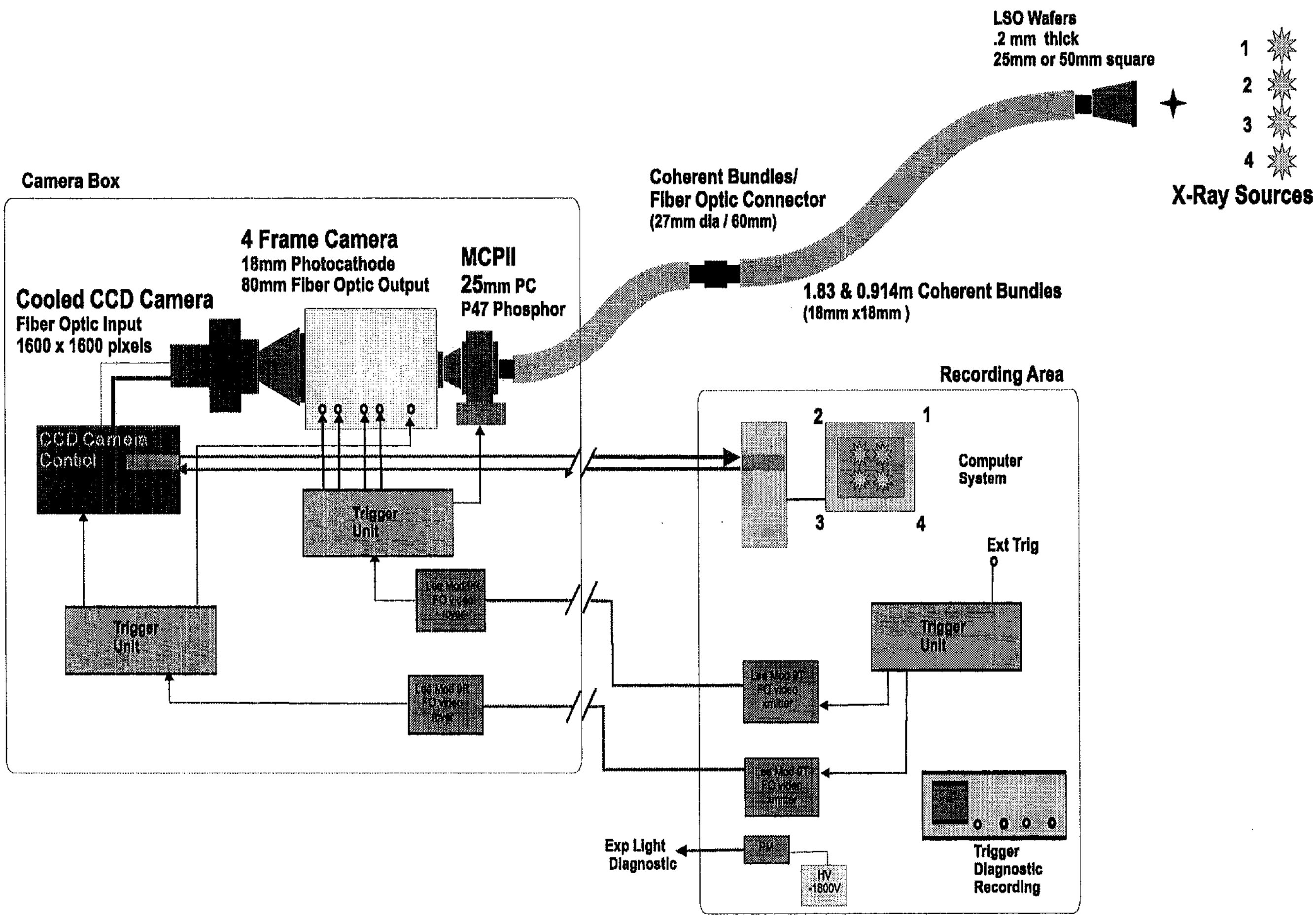

Figure 1. 4-Frame x-ray Imaging System . The four x-ray sources are indicated in the upper right, the object by a "star" and the thin LSO radiation-to-light converter bonded to a fiber-optic taper.

The image relay system is assembled from two coherent bundles[2] (1.89 & 0.94 m) joined by a circular, fused silica rod. The rod serves as a means for reducing the fixed pattern noise associated with the layered fiber assemblies in the coherent bundles as well as for vacuum and shock isolation between the front end of the experiment and the region containing the readout system. The peak emission wavelength of the scintillator is 420nm. The coherent bundles and connecting fiber-optic have been specified to provide the best transmission available in this wavelength region. A gateable micochannel plate image intensifier[3] (MCPII) with a 25mm photocathode(PC) peaked at 420nm and a P47 fast decay output phosphor provides a fiber-optic interface between the image relay system and the 4-image framing camera. The gate period is chosen to cover the total time interval between the 4 X-Ray sources. This results in an enhanced optical shutter ratio between the imaging time interval and external light sources outside this time period (eg light flashes associated with high explosive experiment drivers after the X-Ray images). The gain for the MCPII is adjusted so as not to deplete the microchannel plate charge for the last of the four images, not result in framing tube distortions due to space charge effects, and take advantage of the large dynamic range in the cooled CCD. Operationally this gain is low enough so that with the MCPII turned on its noise floor is not observable in framing camera images with no incident light (dark fields).

The 4-image framing camera in this imaging system utilizes a framing tube developed by IMCO, Ltd.[4] The electronics and mechanical package for the tube were developed by Bechtel Nevada.[5] The fiber-optic input to the framing camera has an 18mm photocathode which is peaked for 420nm wavelength light to match the spectral output from the MCPII P47 phosphor. The square format of the scintillator is transferred to an 11x11mm^2 square input to the framing tube utilizing a fiber-optic taper between the MCPII output and the framing tube input. This taper also provides an electrical isolation between the grounded MCPII output and the 14KV framing tube input. Electronic properties of the framing camera include a 500ns optical shutter period for each of the four images and an interframe time $\geq$ 150ns. The latter is typically between 600ns to 2μs. The optical shutter period is adjusted to capture the scintillator light output from either LSO (40ns) or YSO (80ns). The framing camera has an adjustable optical shutter period as short as 50ns if desired however its resolution is somewhat degraded for periods $\leq$ 150ns. An internal magnification of $\approx$2 provides the best overall performance with little pin cushion distortion and a limiting resolution of about 20 lp/mm on the PC[5]. This results in four $\approx$20mm square images on the output phosphor screen separated by a few mm. The total output image size is therefore 42mm square which utilizes about 60mm of the 80mm diameter fiber-optic output phosphor screen.

A large fiber-optic reducer couples the output phosphor to a Peltier cooled, asynchonously triggered, full frame CCD.[6] The number of pixels in the CCD is $\geq$ 1600 x 1600 to either match or exceed the framing camera resolution. The present system, including X-ray sources with a 50mm square, 250μm thick scintillator, coupled to an 11mm square framing camera PC format and a 1600x1600 pixel CCD results in a limiting resolution of $\approx$2lp/mm (50% modulation of $\approx$1lp/mm). The upper limit to the signal response of this system is driven by the incident X-Ray dose and the lower limit by the noise floor associated with image capture system.

1. The Proton Radiography System

A dynamic radiography facility[7] is currently under development at Los Alamos National Laboratory which utilizes an 800MeV proton beam with variable burst widths and burst interval times (typically 60ns widths and $\geq$ 14 bursts). These multiple bursts permit generating radiographic "movies" of the temporal behavior of explosively driven objects with approximate areal densities between 10mg/cm^2 and 30 g/cm^2. A 60ns burst contains 2 x 10^9 protons which is contained in a gaussian distribution of typically 100mm FWHM selectable by Ta diffuser upstream from the object plane. A lens system distributes the proton beam to precisely match the transfer properties of the magnetic imaging lenses. Each proton burst is imaged with a magnetic lens system from the object plane on to two successive image planes with a magnification –1.0 for the first plane and 1.0 for the second. The image planes are formed by thin LSO scintillator arrays ($\leq$ 2mm thick, 127mm^2) viewed by lens coupled, optically shuttered, cooled CCD cameras. The second image plane utilizes the first image plane as its effective object plane. Each image is usually captured by a single camera system. A variant of the X-Ray framing camera capable of 4 or 9 images is also utilized to replace two of the usual seven single image cameras per image plane if desired. The combination of the two image planes permits up to 21 sequential radiographic images from 21 proton bursts of programmable time intervals $\geq$ 358ns. A precusor proton burst precedes the radiographic bursts by 100us to provide synchronization and phase lock the optical shutters with subsequent beam bursts. A schematic overview of the radiography system and a single camera readout with associated electronic controls is shown in Figure 2. The beam preparation system

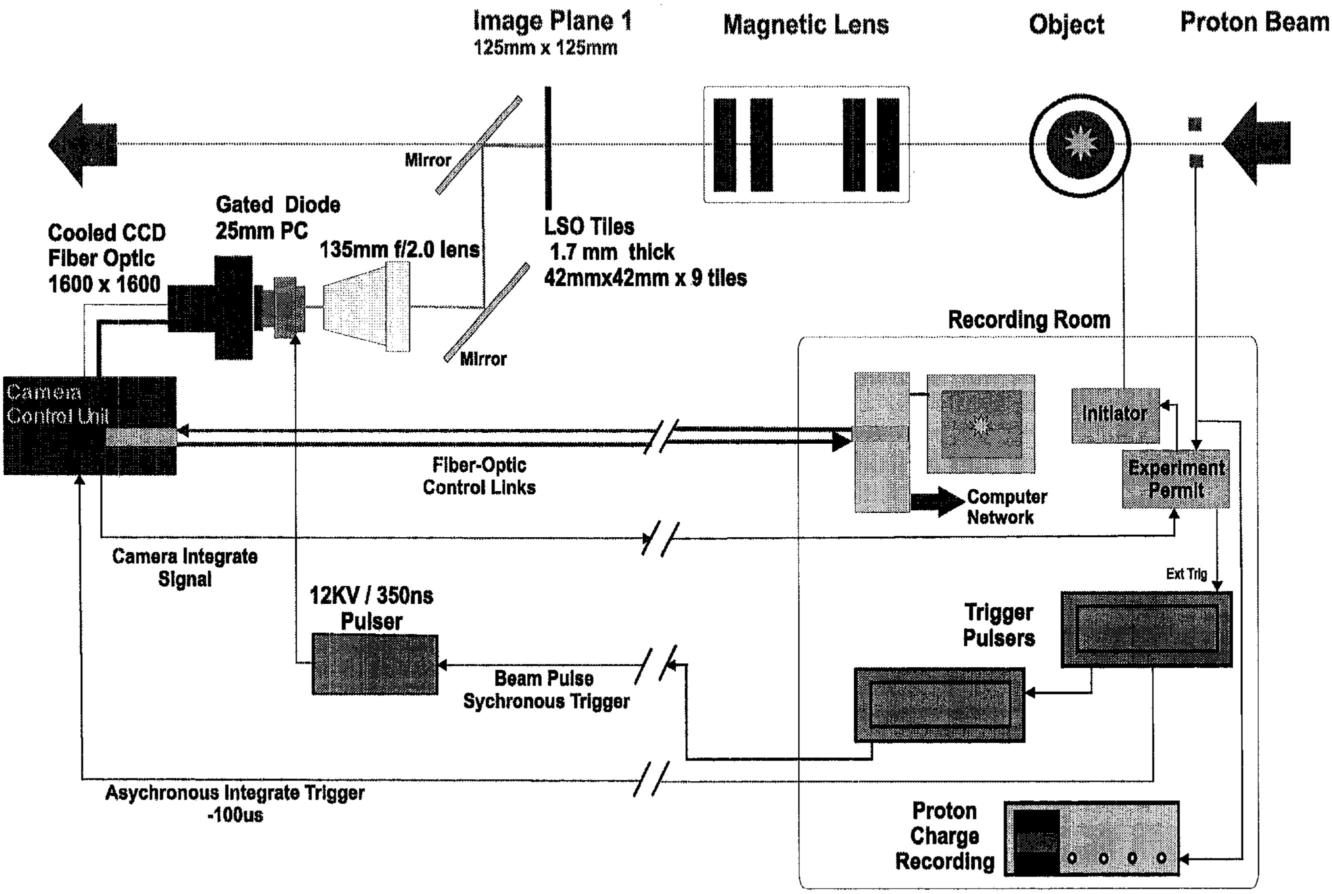

Figure 2. Overview of the proton radiography imaging system. One of seven cameras per image station is shown for multiple proton bursts. Alternatively a 9-image framing camera can replace two single image cameras.

before the object and diffuser are not shown. A proton beam pickoff system (photomultipliers / scintillators and non-intercepting current loop) generates the reference time which is very accurately phase locked to any subsequent radiographic pulses and which is also integrated give the total charge per pulse to better than 3% accuracy. The latter capability permits quantitative areal density determinations through calibration procedures involving a stepwedge data set. A precursor electrical signal is sent from the accelerator timing computer to the data acquistion computer network to arm each CCD camera system ≈25ms prior to the burst of proton pulses from the accelerator. This places the CCD cameras in a continous "flush mode" to reduce dark field current build up. Upon receiving an additional trigger at $-100\mu s$ before the arrival of the proton pulse train into the object, the CCD array is switched in $\leq 25\mu s$ into an integration period of 25ms. Each CCD camera control unit sends out a pulse to confirm it is indeed in the integrate mode. These signals are combined to form a trigger permit to initiate the dynamic experiment. A precisely timed electrical pulse is also sent to the individual triggers for the 12KV, 350ns wide pulsers to sequentially open the electro-optical shutters fiber-optically coupled to the cooled CCDs. The electro-optical shutters[3] are 25mm photocathode, planar diodes with P43 phosphor screens on fiber-optic outputs. The input window is quartz to provide the highest possible quantum efficiency (~15% @ 420nm). Shuttered limiting resolution for these diodes is typically 28 to 30lp/mm for blue light. By varying the delay to the high voltage pulser and keeping the arrival time of the bursts fixed one can empirically determine when the optical gate is centered on the protons. A simple test of the extinction ratio of the optical shutters is to trigger the gates out of time with the protons and compare the signal amplitudes. A timed gate can result in ~30,000 counts above background and for 20 pulses out of time one observes no counts above background giving an extinction ratio $\geq 6 \times 10^5$ since the integration time of the cameras exceed the total time interval of all the proton bursts. Optical gain of about 4 is realized with a 12kV shuttering pulse[8] and 1:1 fiber-optic coupling to the a 5mm fiber-optic wafer bonded to the front illuminated CCD sensors. Some variable gain is possible by adjusting the gating voltage if needed. The camera signal ratio for 12kV to 6kV is 5.5:1 which might be expected due to the internal aluminized coating on the phosphor screen resulting in a photo-electron cutoff near 4.5kV. Statistics indicate a leveling in the image noise for voltages greater than 8kV. This may also be an indication that above this voltage most photo-electrons penetrate the coating screen.

Measured resolution of the entire imaging system with protons is about 2.5 lp/mm with 50% modulation in the scintillator imaging plane and a camera to scintillator magnification of 3.18 or 8 lp/mm at the diode photocathode with a 1600x1600 pixel sensor. Optical resolution for the gated camera system is about 14 lp/mm 50% modulation or 4.4 lp/mm in the scintillator plane. Camera system resolution in the scintillator plane becomes 2.7 lp/mm for a magnification of 5.08

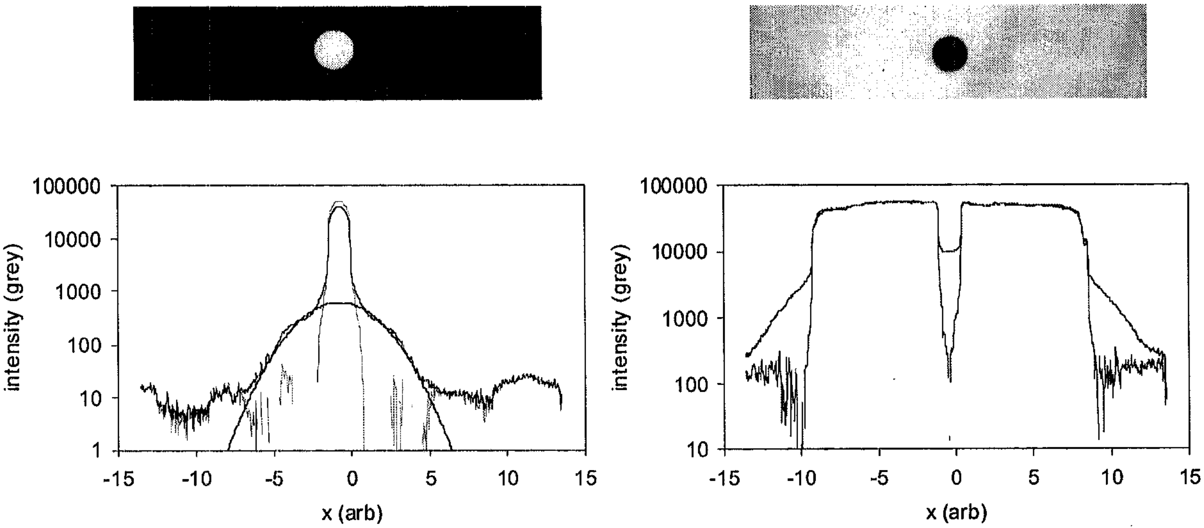

Figure 3. Calibration images to evaluate blurring effects for a circular aperture in a mask at the image plane scintillator and a rod in the object plane. This data is taken with a single proton burst. Both the raw data and the blur corrected data are shown in the lower graphs. The assumed functional form for the correction is shown in the left graph as a solid line.

to achieve the full 127mm field-of-view possible with the magnetic lens system. Other resolution effects are clearly contributors to the overall system resolution. The dynamic resolution is complicated by energy loss effects resulting in a momentum spread in the magnetic lens, shock mitigation requirements, and other sources of proton beam scatter not associated with the object. The current camera system is therefore not the dominant factor in determining the resolution of a proton radiograph.

The effective dynamic range for a gated imaging diode, fiber-optically coupled to a cooled CCD sensor which in turn is lens coupled to the scintillator plane is not well determined by the dark field noise and the full well capacity of the CCD camera. The full well capacity will limit the upper end of the dynamic range and is determined by the number of protons per unit area. The statistical properties of the light emitted from the scintillator in dark regions due to internal light scattering processes coupled with a relatively low diode photocathode quantum efficiency seem to dominate the effective noise floor. Light scatter in the lens system contributes only a few percent to these effects. Estimates[9] of the DQE for this system are between 0.4 and 0.5. This implies the camera system can detect $\leq$ 1 photoelectron / proton and is the result of the high number of visible photons generated per proton for the LSO scintillator ($\leq$ 27000). The lens coupled, gated camera with an optical source is capable of a dynamic range of a few thousand and resolution of 14 lp/mm with 50% modulation at the photocathode. An estimate of the dynamic range can be gauged from Figure 3 before and after a long range blur correction has been applied[10].

3. Performance Limitations

A limitation in the performance of both the x-ray and proton framing camera systems is associated with internal scatter in the fiber-optic coupling to the cooled CCD. The problem arises for a bright image region adjacent to a dim image region in succesive frames where the bright region is in close physical proximity to the dim region on the output phosphor screen. This results in a position dependent "cross-talk" between the images which can be removed by applying a long range blur correction to the composite four frame image[10]. An alternative solution is being investigated with specialty fast lens coupling designs. Improved performance is anticipated for lens coupled framing cameras by replacing the tubes with fiber-optic photocathodes with quartz inputs. The current fiber-optics has poor transmission near 420nm so an improvement of a factor of two in quantum efficiency is anticipated.

Limitations in the gated planar diodes include some sparking due to insufficient ground paths for fast risetime KV pulses and relatively poor resolution (28 lp/mm) for blue light. Possible improvements are being investigated in these areas. An alternative for greater resolution is to complete development of 40mm high voltage gateable diodes or improve gating properties of Gen I 40mm:30mm diodes.

4. Conclusions

The two imaging systems discussed above provide techniques for generating optical shutters for tens of nanoseconds with good dynamic range, high sensitivity and resolution coupled with the advantages of cooled CCD sensors for excellent image quality. The inherent sensitivity of the CCD sensors makes low gain, electo-optic shuttering a viable solution for numerous experimental applications. Both lens coupling and coherent bundle image transfer systems are possible but require different techniques for optimization such as some compromise in light collection efficiency vs resolution due to light scatter.

A fundamental limitation to improving the DQE for the present technology is the low quantum efficiency of photocathodes. Alternative shuttering schemes involving hybrid silicon technology may be a viable alternative in the future. This would combine the advantage of a silicon based readout system with the high quantum efficiency of a solid state photon to electron converter.

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